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# An Indirect Space-Vector Modulated Three-Phase AC-DC Matrix Converter for Hybrid Electric Vehicles

Zhuang Xu*

*The University of Nottingham, China campus, 199 Taikang East Road, Ningbo, 315100, China*

**Abstract**

This paper presents a bi-directional AC-DC matrix converter for the power supply systems of hybrid electric vehicles. Compared to conventional PWM rectifier and associated DC-DC converter, large DC bus capacitor banks are eliminated. The converter converts three-phase AC power into the desired DC output with higher energy density via a single power stage. A closed-loop control strategy based on indirect space vector modulation is proposed and the validity has been verified. The strategy ensures that the output voltage can be regulated tightly against different loads and wide input variation and high-quality input current can be achieved.
Keywords: AC-DC; matrix converter; closed-loop control; indirect space vector modulation

## 1. Introduction

The average electrical power absorbed by the loads of automobiles reaches above 10 kW. In order to pursue constantly high performance, high reliability and intelligence, more electronic equipment is installed in automotive, etc. [1]. Researchers, automobile manufacturers, and parts manufacturers set up the standards of the power nets for automobiles. If the total power remains unchanged, the current can be reduced by 2/3. Considering 10kW for example, 14V power supply system needs wires that can withstand current up to 714A, while the 42V voltage needs wires carrying 238A current [2]. Therefore, it is necessary to implement 42V power supply for automobiles with the developments of technologies. The HEV power train is of the series-parallel type, such as the one found in the Toyota Prius car [1]. This HEV has two kinds of motive power sources: an electric motor and an internal combustion engine (ICE), in order to increase the drive train efficiency and reduce air pollution. The electrical subsystem as shown in Fig.1 is composed of four parts: The electrical motor, the generator, the battery, and the DC/DC converter. However, the three-phase rectifier bridge produces fifth and seventh high order harmonics. The traditional rectifier circuit requires large DC bus capacitors which increase the overall system size and maintenance costs. The alternating current produced first goes through the rectifier and then the chopper Buck circuit and undergoes two-stage power conversion. This reduces the energy transfer density [3].

* Corresponding author. Tel.: +86-0574-88189135; fax: +86-0574-88180175.
*E-mail address:* zhuang.xu@nottingham.edu.cn.


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Considering the above drawbacks of conventional power converters, a novel AC-DC matrix converter is proposed. It has many inherent advantages which power converter cannot compare with. These advantages include [3-5]:

- No large capacity storage devices, fast dynamic response and longer life span
- Wide input voltage range
- Low input current harmonic content and only high-order harmonics
- High power density conversion
- Compact, reduced number of devices in series, highly efficient and easy to be implemented modularly

The new topological structure of the proposed AC-DC matrix converter is derived from three-phase to three-phase matrix converter. The paper [5] records the theoretical study of the AC-DC new topologies, derived AC-DC rectifier control algorithm based on AC-AC modulation, and carried out simulation investigation. The authors in [6] implemented a low power AC-DC matrix converter in the laboratory and obtained sinusoidal input current which is in the same phase with the input voltage. However, input current waveform is not sinusoidal as expected and the switching sequence pattern in the modulation strategy should be further improved. In order to solve electrical isolation problems for the AC-DC matrix converter, the paper [7] introduced high-frequency isolation transformer to the AC-DC matrix converter design and added a rectification transformation. This would reduce the efficiency and lose the benefits of matrix converter.

When the load change is in wide range for the open-loop matrix converter, the output may become unregulated or even unstable. This paper adopts a closed-loop control strategy based on indirect space vector modulation to overcome the downsides of the open-loop control. This paper describes in details the operating principle and closed-loop modulation strategy for the proposed AC-DC matrix converter, verifies its effectiveness, and presents the proven results.

## 2. Operation Principles

Since the maximum voltage modulation ratio of a 3 phase-3 phase matrix converter is 0.866, the matrix converter is generally used as a buck converter. For rectification purpose, the three-phase output in the original three-phase to three-phase conversion can be reduced by one phase and changed into AC-DC matrix converter [5]. The topological structure of the three-phase to three phase matrix converter is shown in Fig. 2 [4].

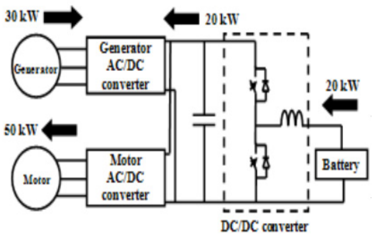


Fig.1. The electrical subsystem of power train systems.

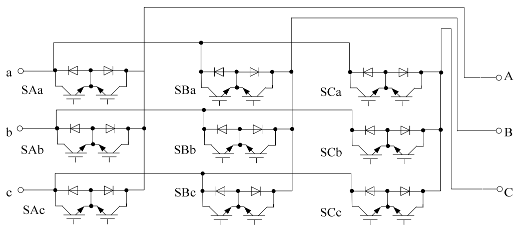


Fig.2. The circuit of 3 phase-3 phase matrix converter

On the basis of the topological structure of matrix converter, its mathematical model as well as its limitations, an AC-DC converter is derived from three-phase to three-phase matrix converter. Its modulation strategy must meet the following requirements: (1) To comply with the matrix converter principle. (2) The output frequency is zero. (3) DC output voltage is equal to the maximum phase voltage.

The AC-DC matrix converter topology, as shown in Fig 3, consists of six bi-directional switches which directly realize the conversion from the input of three-phase AC into the output of DC. The closed-loop control of the matrix converter ensures that the output voltage is tight against different loads and a wide range of input changes.

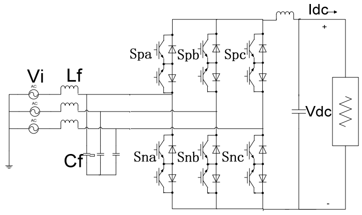


Fig.3. The topology of the AC-DC matrix converter

The bi-directional switch-off states are defined by the function below:

$$S_{jk} = \begin{cases} 1, \mathrm{S}_{jk} & \text{on} \\ 0, \mathrm{S}_{jk} & \text{off} \end{cases} \tag{1}$$

$$\{ j \in (p,n); k \in (a,b,c) \}$$

It is known from the structure of the matrix converter that the inputs cannot be short circuited and the outputs cannot be disconnected. The constraints are:

$$S_{ja} + S_{jb} + S_{jc} = 1 \qquad j \in \{p,n\} \tag{2}$$

The AC-DC matrix converter facilitates a direct AC to DC power conversion without any DC capacitors. This gives more advantages, such as controllable input power factor, highly reliable and compact structure. A space vector modulation method for AC-DC matrix converter is adopted to control the six bi-directional switches.

## 3. Modulation algorithms for the AC-DC matrix converter

Indirect space vector modulation algorithm is based on "virtual DC-link" concept. It regards the matrix converter equivalent in theory to a virtual connection of a rectifier and an inverter. The concept of space vector PWM can be applied to matrix converter and used to modulate the pulse width of "virtual rectifier" and "virtual inverter" respectively. Finally, the two processes were synthesized in order to achieve sinusoidal input and output waveforms and controllable input power factor [6]. The proposed AC-DC matrix converter is deduced with reference to the indirect space vector modulation algorithm. Indirect space vector modulation is divided into two processes. The first stage is the rectification and the other is the inversion process [7]. Fig 4 shows the decomposition diagram illustrating the AC-DC modulation process, which is quite similar to the traditional AC-DC-AC conversion system except that there's no DC bus capacitor. Thus, a DC bus capacitor placed across p and n gives a more virtual illustration of indirect space vector modulation principle.

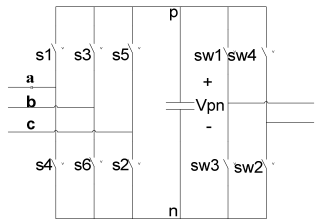


Fig.4. Illustration of the “virtual DC-link" concept.

The process of AC-DC matrix converter can be expressed in the form of mathematical matrix expressions, the virtual DC bus voltage is obtained during the rectification process.

$$V_{pn} = F_r \cdot V_i \tag{3}$$

Where $Fr$ is the transfer function of the rectification pro-cess, while $V_i$ is the three-phase input voltage vector. Output voltage is supposed to be $V_o$, and the expression of output voltage in the inversion stage is shown in (4).

$$V_o = F_i \cdot V_{pn} \tag{4}$$

$F_i$ is the transfer function of the inversion process. Similarly, input line current $I_I$ can be expressed together by the rectification process and the inversion process, as shown in (5) where $I_o$ is the output current vector.

$$I_i = F_r^T \cdot F_i^T \cdot I_o \tag{5}$$

### *3.1. Rectifying Stage*

The purpose of rectification is to obtain a virtual DC bus voltage $V_{pn}$ and maintain the input power factor unity. The DC voltage is modulated by six switches s1 ~ s6 from three-phase input phase voltages. It is known from the principle that the inputs of matrix converters must not be short-circuited. There are six active switching states and three inactive switching states for s1 ~ s6. The space vector hexagon according to the space vector modulation method is drawn as shown in Fig. 5.

Six active switching states correspond respectively to the six switching space vectors in the space vector hexagon. The remaining three inactive switching states correspond to the three zero space vectors. A randomly placed space vector can be synthesized by its two adjacent switching vectors. For example, $V_i$ in Fig.5 is a synthesis of $V_\alpha$ and $V_\beta$, and $\theta_i$ is the angle between $V_i$ and $V_\alpha$. At this moment, switching vector duty cycle can be expressed respectively as follows:

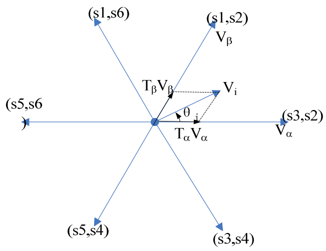


Fig.5 Rectifier space vector hexagon

$$T_\alpha = m_c \sin(60^\circ - \theta_i) \tag{6}$$

$$T_\beta = m_c \sin(\theta_i) \tag{7}$$

$$T_0 = 1 - T_\alpha - T_\beta \tag{8}$$

where $m_c$ is the modulation ratio, $0 \leqslant m_c \leqslant 1$.

Transfer function Fr in the rectification process can be established by means of space vectors through six switching functions s1 ~ s6. The element number of Fr is determined by the numbers of input phases. since it is a three-phase input, Fr has three elements and can be expressed as:

$$F_r = \begin{bmatrix} F_{r1} & F_{r2} & F_{r3} \end{bmatrix} \quad \text{where } F_{r1} = s1 - s4\,;\; F_{r2} = s3 - s6\,;\; F_{r3} = s5 - s2 \tag{9}$$

the displacements between $F_{r2}$, $F_{r3}$ and $F_{r1}$ are −120 degrees and +120 degrees respectively. Below is the expression of $V_{pn}$

$$V_{pn} = 1.5 \cdot m_c \cdot V_m \tag{10}$$

### *3.2. Synthesis Process*

For the six bi-directional switches shown in Fig 3, the logical expression of the six switches can be expressed as

$$\begin{bmatrix} S_{pa} & S_{pb} & S_{pc} \\ S_{na} & S_{nb} & S_{nc} \end{bmatrix} = \begin{bmatrix} sw1 & sw3 \\ sw4 & sw2 \end{bmatrix} \begin{bmatrix} s1 & s3 & s5 \\ s4 & s6 & s2 \end{bmatrix} \tag{11}$$

The AC-DC matrix converter modulation strategy can be implemented by using a DC output voltage outer loop and a current inner loop. The control block diagram is shown in Figure 6.

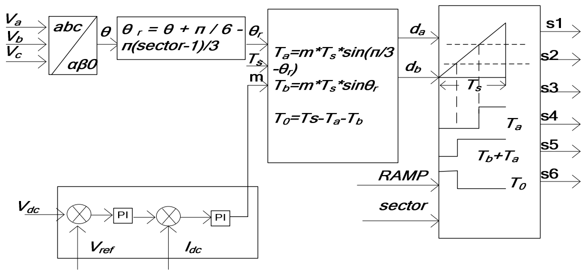


Fig.6 Block diagram of closed-loop control strategy based on indirect space vector modulation

Fig.7. The converter test bench.

The indirect space vector modulation method eases the requirements for the control circuits. This modulation doesn't require the imposition of low-frequency harmonics onto output phase voltage in order to reach the maximum voltage utilization ratio of the matrix transformation device. The arbitrary control of the input current phase differences can be realized.

## 4. Experimental Results

The experimental test rig (Fig.7) has been set up for the three-phase AC-DC matrix converter consisting of bidirectional IGBTs from Eupec. The configuration of the main circuit is illustrated as shown in Fig.3. The controller board deploys TMS320F2812 DSP and Altera MAX II CPLD. Experiments have been carried out to test the closed-loop control strategy that is based on indirect space vector modulation. Fig. 8 (a) plots the waveforms of the input phase voltage $U_a$ and current $I_a$ when the 3-phase AC programmable power supply was set to line frequency of 50Hz and line voltage of 80V. It is seen that $U_a$ and $I_a$ are in phase and the power factor is unity. The DC output $U_{pn}$ and filtered $U_{dc}$ are illustrated in Fig. 8 (b). The smooth $U_{dc}$ has been regulated tightly against the load change. Fig. 8 (c) shows the plots of $U_{pn}$ and $U_{ab}$ where $U_{pn}$ closely follows the top envelope of $U_{ab}$ indicating that due to the switching action, $U_{pn}$ connects and disconnects to the line to line voltage of the supply. When the bidirectional switches were conducting, $U_{pn}$ is generated by $U_{ab}$. To appreciate the advantages of the circuit, more tests have been done to verify the effectiveness. Fig.9 (a) shows that when the frequency and amplitude of the supply were reconfigured to 150Hz and 110V, $U_{dc}$ is still able to be maintained against the load change. Even the frequency and amplitude of the supply decrease further to 25Hz and 50V, the system is still capable of producing satisfactory results as shown in Fig.9 (c).

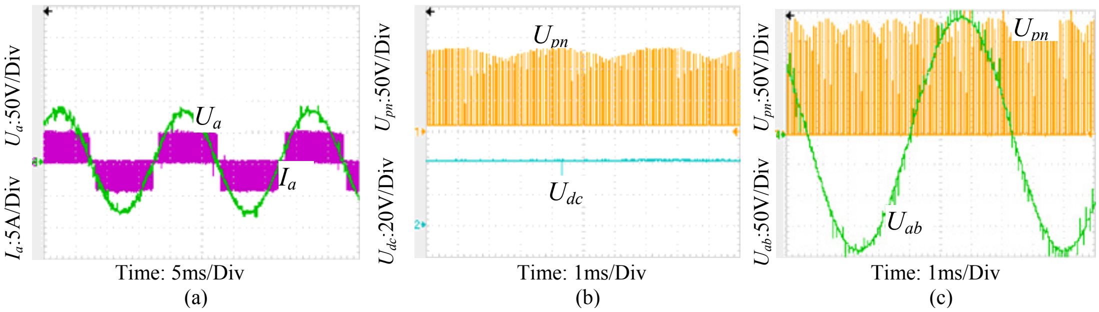


Fig. 8. Input line voltage 80V,50Hz，(a) Phase Ua and Ia (b) Upn and Udc (c) Upn and Uab

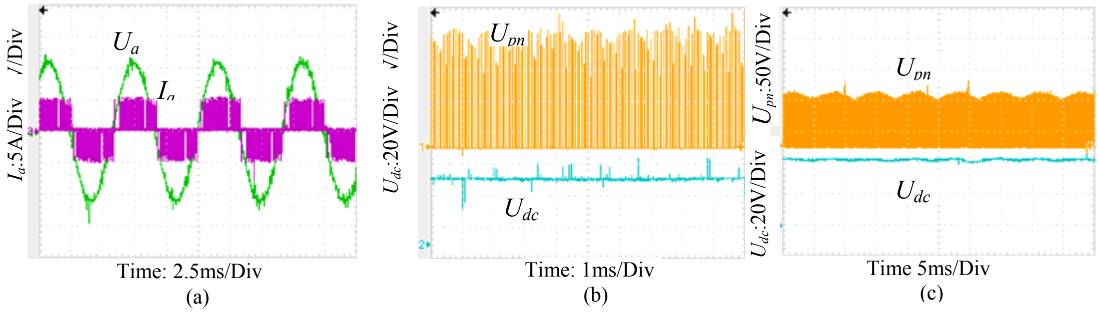


Fig. 9. Input line voltage 110V, 150Hz，(a) Phase Ua and Ia (b) Upn and Udc (c) Upn and Udc @25Hz and line voltage of 50V

## 5. Conclusions

(1). According to the topology and mathematical models of the traditional three-phase to three-phase matrix converters, an AC-DC matrix conversion has been derived.

(2). For the proposed AC-DC converter, a new type of closed-loop control strategy is proposed based on the indirect space vector modulation algorithm.

(3). According to the closed-loop control strategy, experiments have been carried out to verify the feasibility of closed-loop control of the proposed AC-DC matrix converter, which has proved the effectiveness of the proposed system.

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**Biography**

Dr Zhuang Xu works with the University of Nottingham Ningbo China. Zhuang Xu received his Ph.D. degree in electrical engineering from the University of New South Wales, Sydney, Australia. His research has been focused on power electronics and high-performance electrical drives.